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Abstract

Natural gas wells contaminated with the toxic gas hydrogen sulfide (i.e., sour-gas wells) pose potential health risks to workers and to nearby residents. The health risks are a function of the dose-response relationship of hydrogen sulfide, the likelihood of accidental releases, gaseous emission rates, the nature of releases at the well head, dispersion of the emitted gas, and the characteristics of the population at risk. We discuss each of these factors and present a risk analysis of a hypothetical sour-gas well in the vicinity of Evanston, Wyoming. We found that the greatest risks for life-threatening effects would occur in the northwest downwind sector after a horizontal release of gas at the well. Subacute effects (e.g., respiratory irritation) after a vertical release of gas would occur primarily to the northeast. Management of health risks involves the use of techniques for preventing inadvertent releases and methods for limiting population exposures.

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Introduction

Routine emissions of sulfur dioxide, nitrogen oxides, and other gaseous pollutants to the atmosphere have been the subject of abundant environmental research during the past decade. This attention is attributed in part to the potential that such gases have for causing health effects among large populations that receive chronic as well as episodic exposures. Accidental emissions of toxic gases, in contrast, have received far less attention. Though occurring infrequently, accidental emissions can result in acute and subacute health effects among nearby residents. The potential severity of accidental releases of hazardous gases is emphasized by the incident that occurred in 1984 at Bhopal, India, where over 2000 people were killed by exposure to methyl isocyanate, which was accidentally released from a pesticide-manufacturing plant. One way of minimizing health risks associated with inadvertent releases of toxic gases at industrial installations is to quantify the health risks for different types of releases and, importantly, to determine the mix of technologies, procedures, and contingency plans that would effectively manage the predicted risks.

In this paper we assess the health risks of wells that could accidentally release natural gas containing elevated levels of hydrogen sulfide (i.e., sour gas). Sour-gas wells have been completed throughout the world, including several areas of the United States Gulf Coast, parts of Wyoming, and Alberta, Canada. We focus on the risks of wells situated in the Overthrust Belt, a geologic province in western Wyoming and adjoining states, which is characterized by complex thrust faults (see Fig. 1). The health risks of wells completed in such areas are a function of the dose-response relationship of hydrogen sulfide, the likelihood of accidental releases, gaseous emission rates and durations, the nature of releases (e.g., a vertical release into the atmosphere or horizontal to the ground), dispersion of the emitted gas, and the characteristics of the population at risk (e.g., location of residences, susceptibility of individuals to hydrogen sulfide toxicity, etc.). Methods of risk management include various kinds of regulations, contingency plans, and technical measures such as the use of safety valves for limiting gas emissions, corrosion resistant materials for preventing leaks, and gas sensors for detecting the presence of hydrogen sulfide.

Toxic Effects of Hydrogen Sulfide on Humans

Literature on the human health effects of hydrogen sulfide has categorized those effects as acute, subacute, or chronic. Acute intoxication refers to systemic effects, involving both the central nervous system and the respiratory system, caused by a single exposure to elevated concentrations of the gas. Subacute intoxication, on the other hand, refers to the irritative effect of hydrogen sulfide on eyes and the respiratory tract. Chronic effects of low-level exposure consist primarily of odor annoyances and neurasthenic disorders. Table 1 presents a summary of the concentration data associated with the three types of effects.

Acute Toxicity

Hydrogen sulfide is thought to exert its systemic effects by the reversible inhibition of cytochrome oxidase, an enzyme that transfers electrons to oxygen in the chain of enzymatic redox reactions associated with cellular respiration. Inhaled gases, such as hydrogen sulfide and cyanide, bind with cytochrome oxidase with the result that electron transport is blocked and cellular respiration ceases (Lehninger, 1975; Nicholls, 1975). In an aqueous solution, hydrogen sulfide dissociates to hydrosulfide (HS^-) and sulfide ($S^=$), depending primarily on the pH of the solution. However, the undissociated form of hydrogen sulfide is the more effective inhibitor of cytochrome oxidase, and at the physiologic pH approximately one-third of the total sulfide is not dissociated (National Research Council, 1979). Fortunately, hydrogen sulfide absorbed in blood is rapidly oxidized to nontoxic sulfates. Because of this detoxification mechanism and because the inhibition of cytochrome oxidase is reversible, it is regarded as a noncumulative poison. Acute intoxication is believed to result from hydrogen sulfide intake at a rate greater than the body's capacity to oxidize it, leading to perfusion of the central nervous system by undissociated hydrogen sulfide. Nerve centers are first stimulated then paralyzed by the toxic exposure (Evans, 1967). Respiratory collapse or paralysis can occur because of the action of hydrogen sulfide on the nervous system. Another possible mechanism suggested for toxic effects on the respiratory system is through the stimulative action of the gas on the chemoreceptors of the carotid body, an organ that helps to regulate respiratory reflexes based on body chemistry (National Research Council, 1979).

The physiologic response to breathing hydrogen sulfide is governed by the ambient concentration of the gas and by the duration of the exposure (i.e., integral exposure). From our analysis of the toxicology of hydrogen sulfide, we know that acute effects will occur only above a threshold value of concentration because of the body's ability to detoxify this gas. We would expect the threshold value to vary between individuals because of biochemical differences. The health-effects data also show that an increase in ambient concentration is accompanied by a decrease in the duration of inhalation required to induce acute effects. Therefore, to assess the acute effects of an atmospheric release of hydrogen sulfide, we must relate concentrations of the gas (above a threshold level) to exposures that cause acute responses. Unfortunately, few occupational studies dealing with the acute effects of this gas provided data on the concentrations to which the victims were exposed. The minimum concentration and associated exposures that resulted in an acute response (i.e., unconsciousness) were approximately 250 parts per million by volume (ppmv) for a 20-min exposure (Ahlborg, 1951). Data on the exposures that cause acute effects at higher concentrations are derived mainly from studies performed with dogs; one early study showed that dogs have toxic responses to hydrogen sulfide that are similar to those of man (see Mitchell and Yant, 1925). For example, Yant (1930) estimated that the threshold range for acute responses is 500 to 1000 ppmv, based on animal exposures lasting 0 to 2 min. Haggard (1925) found that dogs inhaling air containing 2000 ppmv of hydrogen sulfide would succumb "after a breath or two."

Subacute Toxicity

Subacute intoxication generally refers to sublethal effects involving local irritation of the eyes and respiratory tract, as distinct from the systemic effects of acute intoxication, and is usually associated with prolonged or repeated exposures. At concentrations of approximately 50 to over 100 ppmv, exposure to hydrogen sulfide for about 1 h can produce irritation and inflammation of the eye's mucous membrane (i.e., conjunctivitis) (Yant, 1930). Short exposure to higher concentrations of this gas can also produce eye inflammation. Specific symptoms of ocular damage are photophobia, itching, a sensation of roughness, rainbow phenomena in artificial light, and hazy vision (Beasley, 1963). Moreover, in serious exposures, the cornea can become inflamed (i.e., keratitis). Ahlborg (1951) noted that eye problems can be minimized if the eyes are not rubbed after an exposure, and that the average period of healing was 4 d.

Olfactory paralysis is another subacute effect, and it is manifested at concentrations of 150 to 250 ppmv (National Research Council, 1979). This condition is dangerous because an individual without the sense of smell would not be able to detect potentially lethal concentrations.

Pulmonary edema (excessive accumulation of fluid in the lungs) is the most serious consequence of subacute intoxication (or as sequelae of acute intoxication), because it can result in death. This response to hydrogen sulfide may occur after prolonged exposure (more than 1/2 h) to concentrations of about 400 ppmv and above (Simson and Simpson, 1971).

From a public health standpoint, odor annoyance is probably the most important effect of exposure to low concentrations of hydrogen sulfide.

The median threshold for odor perception is approximately 0.005 ppmv, and about 20% of the population can smell this gas at 0.002 ppmv (Layton et al., 1981; Anspaugh and Hahn, 1980).

Symptoms Following Elevated Exposures

Most of the epidemiological data regarding acute effects are from occupational exposures to elevated levels of hydrogen sulfide. Poda (1966), for example, describes the effects of occupational exposures associated with facilities that produce heavy water by a process that uses hydrogen sulfide as a primary reagent. Of 123 cases of "over exposure" to unspecified levels of the gas at a pilot plant operating for 7 yr, 25 people became unconscious, with 2 requiring artificial resuscitation. During a period of almost 12 yr at another plant, 17 people became unconscious out of 51 overexposures. Four of the unconscious required artificial resuscitation. Unfortunately, no data were available on the concentrations of hydrogen sulfide to which the victims were exposed. Poda notes further that most of the 42 people who became unconscious did not smell the characteristic odor of the gas prior to fainting. Instead, they remembered smelling a "sickening sweet" odor for a brief moment before losing consciousness. Acute exposures of short duration can produce symptoms of an irritative nature typically associated with less toxic exposures. Symptoms commonly observed among the 123 overexposure cases were weakness, nausea, dizziness, headache, nervousness, burning eyes, shock, gastrointestinal upset, and vomiting. Ahlborg (1951) reported on similar symptoms resulting from exposures to hydrogen sulfide in Sweden's shale-oil industry in the middle 1940s.

The most serious incident involving hydrogen sulfide intoxication occurred in 1950 when a flare malfunctioned at a gas desulfurization plant at Poza Rica, Mexico; gas containing 16 vol% hydrogen sulfide was released (see McCabe and Clayton, 1952). Exposure to the released gas lasted about 20 min, and it resulted in the hospitalization of 320 persons and the death of 25. In a sample of 47 patients that were hospitalized, all had lost their sense of smell, half had experienced unconsciousness, 13 had conjunctival irritation, 9 had pulmonary edema, 15 had nausea, and 11 had vomiting. Another pertinent statistic of this tragic exposure is the time sequence of deaths. Of the 25 deaths, 9 individuals were dead on arrival, 8 died within 6 h after hospitalization, and the remainder died after 1 d.

Frequencies of Accidental Gas Releases from Wells

The development of a natural gas well has two distinct phases. The first phase is the drilling of the well, and the second phase is the production of gas for periods as long as 20 yr (assuming the well is successful). These two phases are important in risk analysis because the frequencies and causes of accidental gas releases vary between them. In this section we review and analyze the causes, frequencies, and durations of inadvertent emissions of natural gas from wells in Texas and in Alberta, Canada.

Natural Gas Releases During Drilling

In rotary well drilling, mud is pumped down through the drill string, out the drill bit, and is subsequently returned to the surface via the annulus (i.e., the area between the drill pipe and the wellbore or casing). At the surface, the formation cuttings are removed and the processed mud is recirculated. Primary functions of the drill mud include the removal of formation cuttings, lubrication and cooling of the drill string and drill bit, and the control of subsurface pressures. The downhole hydrostatic pressure exerted by the mud is kept higher than the pressure of the formation fluids at depth to prevent movement of those fluids into the wellbore. Flow of gas into a well because of a pressure imbalance (i.e., formation pressure is greater than drilling fluid hydrostatic pressure) lowers the density of the drilling fluid and causes a corresponding increase in the volume of drilling fluids in the mud pit or tank (Goins, 1969). This condition is referred to as a kick, and if it is not controlled, a blowout may result.

Kicks are often associated with the improper pulling of drill pipe from the wellbore or running a pipe into a well (i.e., a trip). Removal of drill pipe can create a swabbing effect that produces a pressure differential great enough to allow formation fluids to enter the wellbore. In addition, if the hole is not properly filled with drilling fluid to compensate for the volume of the pulled drill pipe, the resulting pressure decline can induce the flow of formation fluids to the wellbore. Kicks can also happen when the circulation of drilling fluids is lost due to movement of those fluids into a porous or fractured zone. A sharp increase in formation pressure compared to the pressure of the drilling fluid, caused by penetration of a high pressure gas zone, is another source of well-control problems. An accelerated rate of drilling, known as a drilling break, can also signal the onset of a kick.

We reviewed data on the causes of 83 blowouts of natural gas wells in Alberta, Canada, during 1960 through 1980 and found that 57% of the blowouts occurred during trips (Energy Resources Conservation Board, 1981a; 1981c). Most of those releases were attributed to either the swabbing action of the drill pipe, insufficient mud weight, failure to keep the well full of drilling fluid, or a combination of the three. In addition, about 10% of all releases occurred during drilling when the weight of the mud was not enough to prevent the influx of formation gases. Other blowouts resulted from penetration of high-pressure gas zones (12%), lost circulation (11%), and equipment failures together with other miscellaneous or unknown causes (11%). These data emphasize the potential for uncontrolled conditions developing during removal or insertion of drill pipe in a well.

Between 1960 and 1980, 24,660 productive gas wells were drilled in Alberta in addition to 12,602 productive oil wells, 19,001 dry holes, and 3,950 miscellaneous wells. Most of the natural gases there are contaminated with hydrogen sulfide. The probability of a new gas well blowing out can be estimated from the historical data by dividing the number of blowouts by the sum of the productive gas wells and dry gas wells. The blowout probability is not simply the ratio of blowouts to productive gas wells, because the resulting probability would only be applicable for estimating the chances of a blowout for a producing well; we do not know in advance whether a well will be productive or not. Furthermore, we cannot assume categorically that wells that are determined to be "dry" in a commercial sense are incapable of having blowouts. The number of dry or unproductive gas wells can be calculated by assuming that the ratio of productive gas wells to the sum of all productive wells is the same as the ratio of dry gas wells to the total number of all types (i.e., oil, gas, and miscellaneous categories) of dry wells, which is the reported statistic.

We define a blowout as any accidental, uncontrolled release of gas to the atmosphere. This definition was employed because, in many instances, estimates of the amount of gas released were unavailable, and consequently, it was not possible to classify releases as large, small, or insignificant. We also excluded wells that were not clearly identified in the records as gas wells. Many of the wells in Alberta produce sour gas, but we did not treat them as a separate class because data were lacking on hydrogen sulfide concentrations in these wells. Eighty-three releases were defined as blowouts using this classification method.

The total number of productive and unproductive gas wells from 1960 to 1980 was 35,076, and the frequency of blowouts was equal to 83/35,076 or 2.4×10^{-3} blowouts per gas well drilled. For the period 1970 to 1980, the probability was 1.6×10^{-3}. To obtain data allowing us to quantify the blowout frequency for gas wells drilled in Texas, we reviewed files of the Texas Railroad Commission (Railroad Commission of Texas, 1982). For 1977 through 1981, 99 uncontrolled gas releases occurred for 26,850 gas wells drilled; this latter figure included 8,278 wells classified as dry (using the approach described above) and 18,572 reported as productive. The blowout frequency is therefore 3.7×10^{-3} blowouts per gas well. Even though this frequency is more than a factor of 2 higher than the blowout frequency calculated using data from Alberta, the frequencies are similar.

Though we cannot explain fully the difference between the estimates, we note that the geometric mean depth (1360 m) of the Texas wells with uncontrolled releases was about 25% greater than the depth (1090 m) of the Alberta wells. We would therefore expect a higher frequency of blowouts in Texas, because longer trips would be required to extract drill pipe from wells, increasing the chances of uncontrolled flow conditions. Other factors affecting the blowout frequencies may include drilling regulations (e.g., rules governing the drilling of sour-gas wells), different drilling practices and equipment, the presence of overpressured gas formations, and the experience of drill crews.

Natural Gas Releases During Gas Production

We also calculated the frequencies of accidental gas releases from completed wells, including both shut-in wells and producing wells in Alberta and Texas. The 1960 to 1980 data for Alberta show that 43 accidental releases occurred over 117,320 well-yr of operation, representing a rate of 3.7×10^{-4} releases per well-yr. For 1970 to 1980, based on 36 events and 100,126 well-yr, the rate was 3.6×10^{-4} releases per well-yr. Over the total period, 15 of the 43 accidental releases (35%) resulted from problems encountered during the servicing of wells. Of the other 28 releases, 13 were caused by external damage (typically a caterpillar tractor running over a well head). Miscellaneous equipment failures (e.g., valve failures, poor cement jobs, etc.) accounted for most of the remaining releases. It is worth noting that hydrogen sulfide was not identified as a cause of any of those failures. The Texas data for 1977 to 1981 show that

9 accidental releases occurred over 177,323 well-yr of operation, which is equivalent to a rate of 5.1×10^{-5} releases per well-yr, and which is only 14% of the rate calculated for completed wells in Alberta. Using these rates, we calculate that a completed well in Alberta would have a 7.2×10^{-3} probability of accidentally releasing gas to the atmosphere over a 20-yr period compared with a probability of 1×10^{-3} for a completed well in Texas. The geometric mean value of the rates for Alberta and Texas is 1.4×10^{-4} releases per well-yr; over a 20-yr period the probability of a release becomes 3×10^{-3}.

These calculations indicate that the probability of a gaseous release during the drilling phase of development is comparable to the probability of a release over the entire production or post-completion phase. We emphasize further that the blowout probabilities we have calculated are for both sour and natural gas wells, and consequently, the results may not necessarily provide an accurate prediction of the likelihood of an accidental release from a sour-gas well. At this time we cannot state whether sour-gas wells are more or less likely to have accidental releases. For example, sour gas can cause metallurgical problems (e.g., stress cracking, embrittlement, corrosion, etc.), which may enhance the chances of a well failure; however, special alloys are specified for use in hydrogen sulfide environments to avoid such problems. Corrosion inhibitors provide additional protection against such problems. Moreover, sour-gas wells, like those being completed in the Overthrust Belt, are usually equipped with special safety valves that reduce the chances of an accidental release. During drilling, special precautions are taken before and during the penetration of sour-gas formations. Despite these measures, human errors, equipment failures, etc. can still cause accidental releases.

Duration of Blowouts

Another important statistic is the duration of the blowouts. This parameter can be useful in planning for emergency responses needed in the event of a well blowout. Data on blowouts in Alberta and Texas show that releases last from less than an hour to several months (Energy Resources Conservation Board, 1981c; Railroad Commission of Texas, 1982). More commonly, though, releases last a few days. The geometric mean of durations of the Alberta blowouts is 1.8 d compared to 3.2 d for those in Texas. When the data for the two areas are combined, the geometric mean is 2.4 d, with a geometric standard deviation of 4.5.

Estimating Hydrogen Sulfide Emission Rates

To assess the hazards associated with a release of hydrogen sulfide to the atmosphere, it is necessary to estimate the hydrogen-sulfide emission rate. Such an estimate depends on the gas-discharge rate from the source and the concentration of hydrogen sulfide in the discharged gas.

Gas Discharge Rates from Wells

The uncontrolled flow of gas from a well is governed by properties of the gas reservoir and the flow string (i.e., the pipe or casing through which the gas flows). Figure 2 is a simplified diagram of a completed well that shows the pertinent features of a reservoir/well system. Gas flow through the formation and into the wellbore is controlled primarily by the properties of the reservoir, including the permeability of the producing formation and its thickness; the geometry of the reservoir; and the pressure, temperature, and composition of the sour gas within the reservoir. Data on these parameters are acquired from well logs, flow tests, and gas analyses made while the well is being completed. One measure of the potential productivity of a well is termed the calculated absolute open flow (CAOF), or the flow rate of gas into a wellbore when atmospheric pressure is present at the sand face of the producing formation. The CAOF is never attained, though, because the frictional resistance of gas flowing through casing or tubing to the surface creates a downhole pressure that is greater than atmospheric pressure. The flowing subsurface pressure is a function of gas properties; the interior diameter, length, and friction factor of the flow string; and the surface pressure against which gas is discharged (assumed to be atmospheric pressure under blowout conditions). The subsurface pressure is especially sensitive to the interior diameter of the flow string; that is, as the diameter decreases, the frictional resistance to a constant flow rate of gas increases. We used an analytical equation to calculate subsurface pressures for a liner or casing (16.2 cm, interior diameter) and for a production tubing (6.1 cm, interior diameter). We found that the uncontrolled flow of gas through a production casing or liner will not produce downhole pressures that greatly inhibit the flow of gas from a formation to a well (Layton et al., 1983). Hence, the CAOF represents an upper-bound estimate of the unrestricted, atmospheric discharge of gas from a well that does not have its production tubing in place. With the production tubing in place, however, the flow resistance associated with the smaller diameter pipe causes a downhole pressure that results in an atmospheric discharge that is about 40% of the CAOF. For a completed well, the smaller flow rate represents a practical upper-bound emission rate of gas to the atmosphere for normal production conditions. During well servicing with tubing out of the well, though, the CAOF would also be appropriate.

Hydrogen Sulfide Emissions from Uncontrolled Wells

The mass emission rate of hydrogen sulfide from an uncontrolled sour-gas well is equal to the product of the volumetric flow rate of the gas emitted to the atmosphere and the concentration of hydrogen sulfide in the gas expressed in units of mass per unit volume. In mathematical terms,

$$Q = C \cdot D \, , \tag{1}$$

where

Q = emission rate of hydrogen sulfide, g/s;

C = concentration of hydrogen sulfide in emitted gas, g/m^3; and

D = gas flow rate, m^3/s.

Calculation of the potential emission rate of hydrogen sulfide from a completed well is a straightforward procedure after flow testing is completed and analyses of hydrogen-sulfide gas have been obtained. Estimating emissions from an uncompleted well is more complicated because of the uncertainties associated with the parameters C and D. The effect of those uncertainties on the estimation of Q can be dealt with by propagating the uncertainties (i.e., statistical variances) of C and D to obtain the uncertainty associated with Q. Because Eq. 1 is multiplicative, the uncertainty can be quantified analytically if we assume that C and D are lognormally distributed and that they are independent. The variance of Q is then calculated as

$$\ln^2 \sigma_g(Q) = \ln^2\sigma_g(C) + \ln^2\sigma_g(D) , \tag{2}$$

where $\sigma_g(Q)$, $\sigma_g(C)$, and $\sigma_g(D)$ are the geometric standard deviations of the variables.

Our analyses of the data on hydrogen sulfide indicate that an estimate of the concentration of hydrogen sulfide expected in the natural gas from a new well should be based on concentration data derived from nearby wells completed in the same target geologic formation or formations. If a wildcat well is to be drilled in an area where such data are absent and the subsurface geology is poorly defined, the best way to estimate the concentration is to use the distribution of the pooled hydrogen sulfide concentrations from sour-gas wells located in different fields and completed into several formations. We therefore collected data on the hydrogen sulfide concentrations in gases obtained from wells completed in several different geologic formations.

In Table 2 we have summarized statistically the data we obtained on the concentrations of hydrogen sulfide in natural gases from wells in the Overthrust Belt. Concentrations range from below 1 mol% (14 g/m^3) in the Bighorn formation to about 35 mol% (504 g/m^3) in the Madison formation. Because of the small sample sizes for each of the formations listed in Table 2, we were unable to find superior fits for either the normal or lognormal distributions. Accordingly, we present the statistics for each distribution. In addition to those data, one measurement was obtained for the Dinwoody Formation of 4 mol% (58 g/m^3) and two for the Darby Formation of 9 and 9.8 mol% (130 and 141 g/m^3). The geometric mean of the lognormal distribution of the pooled concentration data is 6.9 mol% (100 g/m^3) with a geometric standard deviation of 3. To estimate gas discharges, we collected data on the CAOF of 15 wells (Moore, 1982) completed at depths of between 2700 and 5500 m in western Wyoming (depths where essentially all of the sour-gas formations are located). The geometric mean of the distribution was 1.3×10^5 m^3/d with a geometric standard deviation of 4.7. The geometric mean of Q is therefore 150 g/s with a geometric standard deviation equal to 6.7; i.e., $\sigma_g(Q) = \exp[(\ln^2 3 + \ln^2 4.7)^{1/2}]$.

Predicting Downwind Dispersion of Gas

Field personnel estimating the extent of hazard zones around sour-gas facilities typically have used screening equations that are solutions to the Gaussian diffusion equation. Such screening equations are relatively easy to apply; however, there are issues involving the accuracy of the predictions and the applicability of the underlying diffusion equation for different meteorological and topographical conditions. Despite some of the limitations of this steady-state model, it still represents a valuable tool for screening applications--especially in situations where the uncertainties associated with the estimate of the gas-emission rate and the nature of the release (i.e., vertical or horizontal) are frequently of the same magnitude as the uncertainties associated with the Gaussian model. For example, over all atmospheric conditions, Gaussian models can be expected to predict nearly all short-term (10-min) concentrations within a factor of 10, with most values falling within a factor of 2 to 5. In contrast, the geometric standard deviation of the CAOF for wells in the Overthrust Belt is nearly 5, which means that 68% of the gas discharge rates are within a factor of 5 of the geometric mean. Moreover, according to a sensitivity analysis we performed on the effect of plume height on predicted concentrations, an error in the specification or prediction of plume height can produce a difference in computed concentrations by a factor as high as 10 (Layton et al., 1983). A key uncertainty in the estimation of downwind concentrations of hydrogen sulfide following an accidental release is the effective height of the plume of dispersing gas. We handled this uncertainty by dividing releases into two categories: elevated emissions, in which gas is discharged vertically in the atmosphere (a momentum-dominated plume rise), and near-surface releases, where gas is discharged horizontally. These two conditions bound the cases that can occur.

Vertical Releases

The upper-bound estimate of a CAOF should only be used in a screening equation that includes plume rise. The CAOF is based on discharge through the completely open casing, which means that the discharge at the surface is unrestricted. Under those conditions, the gas is emitted at sonic velocity from the well, and a momentum-dominated rise of gas into the atmosphere is produced. The Gaussian dispersion equation can be used to calculate the ground-level concentrations of gas along the centerline of a plume of dispersing gas:

$$\chi = \frac{Q}{\pi u \sigma_y \sigma_z} \exp \left[\frac{-0.5\ h^2}{\sigma_z^2}\right] \quad , \tag{3}$$

where

χ = ambient concentration of gas, g/m^3;

Q = gas emission rate, g/s;

σ_y = standard deviation of gas concentration in cross-wind (y) plane at a given downwind distance, m;

σ_z = standard deviation of gas concentration in vertical (z) plane, m;

u = mean wind speed at the height of the plume, m/s; and

h = effective height of the plume, m.

The plume rise Δh is calculated from the following equation:

$$\Delta h = 205\ u^{-0.96} \quad , \tag{4}$$

where Δh is in meters and u is in m/s, measured at 2 m. This function was derived empirically from a series of pipe-burst studies performed under the auspices of the Alberta Petroleum Industry (1979), Government Environmental Committee on Hydrogen Sulfide Isopleth Prediction. According to this relationship, the rise of a momentum-dominated plume decreases as wind speed increases, causing the plume to be bent over. The effective plume height h is then the actual release height plus plume rise Δh. The values of σ_y and σ_z for different downwind distances and atmospheric stabilities can be estimated from empirical relationships presented by the Texas Air Control Board (1979). These relationships are of the form $\sigma_y = ax^b$, where x is downwind distance and a and b are specified for different stabilities. Tables 3 and 4 contain the power law coefficient for calculating σ_y and σ_z. Because of the dispersion occurring before the plume reaches the ground, the health effects associated with vertical releases are most frequently of a subacute nature. The maximum concentration is higher, and the distance associated with it is closer to the source, for higher winds that limit plume rise and for more unstable conditions that mix the plume down to the ground more quickly.

Horizontal Releases

Under stable atmospheric conditions and a low wind speed, a horizontal discharge of sour gas represents a worst-case release scenario; high concentrations of hydrogen sulfide would occur as the plume slowly dispersed near the ground. The principal safety concern from this type of release is the potential for acute, life-threatening health effects, including respiratory arrest and unconsciousness. An important uncertainty for horizontal releases is the effective rise of the plume. A horizontal release of sour gas at sonic velocity would produce a turbulent jet of gas that would interact with the ground surface. Consequently, the center of mass of the resulting plume would be at some elevation above the release point. It is not possible to predict accurately the actual height to which this type of plume rises, because no experiments have addressed this situation directly. For conservative, yet realistic, screening calculations (using Eq. 3) we have chosen a height of 5 m to represent the plume rise for horizontal releases.

Quantification of Health Risks From an Accidental, Continuous Release of Sour Gas

The probability that a person living near a sour-gas well will incur an adverse health effect (i.e., health risk) after an accidental gas release can be calculated. It is the product of the probability that the well will accidentally release gas to the atmosphere during a certain time period and the sum of the effect probabilities associated with such a release occurring randomly among different meteorological conditions; such conditions are defined by six wind-speed classes, seven atmospheric stability categories (see Table 5), and 16 wind directions (i.e., each wind sector is 22.5°). The basic equation for calculating the health risk at a fixed location (i.e., receptor) near a sour-gas well is

$$R_k = P_r \sum_{j=1}^{7} \sum_{i=1}^{6} T_{ij} \, O_{ijk} \quad , \tag{5}$$

where

- R_k = risk of a health effect at a fixed distance in downwind sector k,
- P_r = probability that an accidental release occurs,
- i = subscript representing wind-speed class,
- j = subscript representing the atmospheric stability category,
- T_{ij} = probability of a toxic response to inhaling air that contains a concentration of hydrogen sulfide that is predicted with stability category j and wind-speed class i at a fixed distance downwind in wind sector k where the receptor is located, and

O_{ijk} = joint probability of stability class j and wind-speed class i occurring simultaneously in wind sector k where the receptor is located.

Variations of this method of calculation have been described by Ledbetter (1978) and Atwell and Andrews (1979). Ambient concentrations are computed for each of the 42 combinations of wind speed and atmospheric stability for the downwind sector where the receptor is located; then, to calculate T_{ij}, the predicted concentrations are related to the probability of a person experiencing a health effect by a dose-response function. That estimate is multiplied by the joint frequency of wind speed, atmospheric stability, and wind direction (i.e., O_{ijk}) that is used to compute the ambient concentration of hydrogen sulfide at the receptor. Conservatively, we assume that if the wind direction is within a 22.5° sector, the plume centerline will directly impact a receptor in that sector. To support those calculations, data are needed on the joint frequencies of wind speed and atmospheric stability for different wind directions and the relationship between concentration and effect.

Risk Analysis of a Hypothetical Well near Evanston, Wyoming

We have applied the health-risk methodology to future exploratory wells that might be drilled near Evanston, Wyoming, an area where sour-gas development has occurred. To establish the joint frequency distribution defining O_{ijk}, we installed four meteorological stations in and around Evanston to characterize the dispersion meteorology of a broad area where sour-gas wells could be established. Over a 1-yr period we collected measurements on wind speed, wind direction, and air temperature at each of the stations. Several features of the local meteorology that directly affect the areal distribution of health risks are worth noting. First, the data show that the winds associated with stability class F are predominately of low speed and from the southeast. Second, low wind speeds are also associated with stability classes A and E. Classes B, C, and DD have winds that are primarily from the west and southwest at moderate to high speeds. Finally, we found that stability classes A, DN, and E were spread across more wind directions than the other stability classes.

The calculation of the probability of a toxic response, T_{ij}, at a fixed distance downwind from a well requires the estimation of an ambient concentration, χ, at that location and the calculation of the probability that an effect would occur given the predicted concentrations. Unfortunately, we were not able to construct a dose-response function relating hydrogen sulfide concentrations and exposure periods to effect probabilities. Instead, we calculated a threshold concentration above which the probability of an effect was assumed to be 1. The concentrations predicted by the Gaussian dispersion equation are for a period of approximately 10 min, corresponding to the duration of the σ_y and σ_z values. We therefore had to determine a 10-min concentration that constitutes an effects threshold. Literature on the toxicology of hydrogen sulfide suggests that thresholds should be defined for both acute and subacute (i.e., sublethal) effects to ensure that risk-management alternatives (e.g., contingency plans) are prepared that specifically address the health care requirements for the two types of effects.

We defined an acute effect as either unconsciousness, respiratory arrest, or death following exposure to hydrogen sulfide. The best data we have for estimating a threshold for unconsciousness indicates a concentration of about 250 ppmv over a 20-min exposure (Ahlborg, 1951). To relate this to a 10-min exposure, we used the following empirical relationship (Cremer and Warner Ltd, 1979):

$$L = C^{2.5}M , \tag{6}$$

where

L = a constant;

C = gas concentration, ppmv; and

M = time, min.

If C equals 250 ppmv and M equals 20 min, then L equals 2×10^7. With M equal to 10 min and L equal to 2×10^7, the value of C becomes 330 ppmv, assuming that L is essentially constant over different concentrations and exposure periods. For our analysis, we set the threshold for acute effects at 300 ppmv or 0.345 g/m^3 (χ is converted to ppmv by multiplying it by 869 ppmv $\cdot$ m^3/g, which is based on an elevation of 1830 m and an ambient temperature of 15.6°C). Thus, T_{ij} equals 1 for all values of χ greater than or equal to 300 ppmv; for values of χ less than 300 ppmv, T_{ij} equals 0. We chose 50 ppmv as the threshold for subacute effects because, above this concentration, exposed individuals begin to experience effects that require attention, such as irritation of the eyes and respiratory tract. In addition, an intense odor of hydrogen sulfide becomes apparent in the air. The combination of these symptoms might also cause emotional stress among exposed individuals.

Health Risks for a Horizontal Release

In our analysis of the health risks of an exploratory sour-gas well accidentally discharging gas horizontally into the atmosphere during drilling operations, we first estimated a release rate for hydrogen sulfide. Specifically, to minimize the error of underpredicting the areal extent of toxic downwind concentrations, we wanted to determine a rate that had a small probability of being exceeded. The upper-bound estimate of the hydrogen sulfide discharge rate was calculated by multiplying the previously calculated geometric mean of emission rates (150 g/s) by 6.7^2, which equals 6700 g/s. This value corresponds to the 98th cumulative percentile on the lognormal distribution of discharge rates, defined by the geometric mean and standard deviation. Next, we multiplied this rate (based on CAOF) by 0.4, a factor used to account for the flow through the smaller diameter pipe associated with a horizontal release. Figures 3 and 4 are plots of the risks of acute health effects vs downwind distances in four wind sectors (i.e., Fig. 3 includes the N, NE, E, and SE downwind sectors, whereas Fig. 4 includes the NW, W, S, and SW sectors). These risks are based on the assumption that a release has actually occurred (i.e., the risks represent conditional probabilities, with P_r equal to 1). Therefore, to obtain an estimate of the actual health risks, each point on the curve must be multiplied by the probability of a release during the particular phase of drilling that is being assessed (for the purposes of the risk analyses we assume that the annual joint probabilities of wind speed, atmospheric stability, and direction are indicative of the average conditions associated with either drilling or production). According to our analyses on the frequencies of blowouts, the probability of a blowout during drilling is approximately 1×10^{-3}. This value can be considered an annual probability because it can take as long as a year to complete a well. If the points on the curves in Fig. 3 are multiplied by this value, the risk of acute health effects exceed 10^{-4} in the immediate vicinity of the well, but rapidly decrease to values between 10^{-5} and 10^{-4} in the four downwind sectors. In Fig. 4, however, it is indicated that the risks in the NW downwind sector exceed 10^{-4} because of the joint occurrence of stable atmospheric conditions and low wind speeds from the southeast. The curves are truncated at a distance of about 2.3 km because this is the maximum distance to the threshold concentration (i.e., 300 ppmv) for acute effects, as predicted by the Gaussian dispersion equation for the assumed emission rate and effective release height of gas (i.e., 5 m). Another important consequence of a horizontal release is the subacute effects that would accompany the acute effects. Our analysis of these effects shows that risks of subacute effects on the order of 1×10^{-4} would extend beyond 5 km from the release point to receptors located in the northern downwind sectors. The risks of subacute effects in the southern downwind sectors were mainly below 10^{-5}.

What is the significance of these risk levels? One way of answering that question is to compare them with other risks. According to data in Coppola and Hall (1981), approximately 100,000 accidental deaths (e.g., caused by motor vehicle accidents, poisonings, falls, fires, etc.) occur in the U.S. each year. This number translates to an individual risk of 5×10^{-4}/yr (i.e., 1×10^5 deaths divided by a population of 2×10^8). In contrast, the risk of accidental deaths caused by natural disasters is on the order of 7×10^{-6}/yr. If we accept the risk of death from a natural hazard as a reasonable baseline for comparison, then the NW downwind sector is at excess

risk for acute effects, whereas most of the downwind sectors would have relatively high risks for subacute effects. However, it should be recognized that these risk values represent upper-bound estimates for the following reasons: (1) an accidental blowout could also result in a vertical release of gas, resulting in lower ground-level concentrations of hydrogen sulfide, especially in situations where provisions have been made to ignite the escaping gas (e.g., as specified in contingency plans for drilling); (2) the combusted gas would not cause acute effects; (3) the operation of safety valves on the well would produce a transient release of gas rather than a continuous release, assuming they operate properly; and (4) the actual frequency of blowouts in the Overthrust Belt could be lower than the value we used.

Health Risks for a Vertical Release

A vertical release of gas from a well does not produce downwind concentrations of gas that are high enough to cause acute effects, even at the upper-bound discharge rate used for unrestricted, vertical discharges (i.e., 6700 g/s of hydrogen sulfide). However, according to our calculations, concentrations above 50 ppmv would occur in all of the downwind sectors except one (i.e., the SW sector). In the NW wind sector, concentrations above 50 ppmv extend more than 3 km downwind. The probabilities of sublethal effects in that sector, given that a release has occurred, are shown in Fig. 5. The relationship of the effect probabilities and distance depends almost entirely on wind speed. As wind speeds increase, the plume is nearer the ground because of reduced plume rise (see Eq. 4), and therefore, ground-level concentrations are higher. Near the source, only a portion of the plume reaches the ground surface, resulting in lower effect probabilities in that region.

Implications for Risk Management

A primary purpose for analyzing and assessing potential health risks of an accidental release of sour gas is to understand the nature, magnitude, and distribution of risks so that methods can be devised to manage unacceptable or undesirable risk levels. Methods for managing risks can be divided into two broad categories: (1) measures for preventing or limiting gaseous releases to the atmosphere, and (2) measures for dealing with the consequences of an inadvertent release.

Prevention and Limitation of Gas Releases

Our review of the causes of well blowouts during drilling and production in Alberta, Canada, indicates that a combination of technical and human factors have contributed to releases; therefore, the risk-management methods must address both areas. For drilling operations, it is evident that human factors are an important aspect of blowout prevention.

For example, training and experience related to the use of drilling mud to maintain subsurface pressures is perhaps the single most important measure to prevent gas releases from wells drilled in the Overthrust Belt and thereby to reduce health risks. For the sample of Alberta wells, more than half of the releases during gas production were caused by problems associated with well servicing and external damage. Risk-management studies should be directed, therefore, toward identifying remedial actions for preventing releases during servicing and, importantly, for reducing the number of well-servicing operations in general. Also, methods of physically preventing access to wells, such as concrete barriers and fences, would reduce the frequency of releases that are accidentally caused by heavy equipment and even vandalism. Such measures together with the safety valves, special alloys, and corrosion inhibitors already used with sour-gas wells should greatly reduce the likelihood of releases.

Post-Release Measures

Post-release measures for managing health risks are designed to minimize human exposures to sour gas and to deal with any adverse health effects that might occur. Population exposures can be limited in various ways. For example, if the risk analysis of the hypothetical well had shown sensitive receptors (e.g., residences, roads, schools, etc.) in the NW downwind sector, then the well could be sited to reduce the predicted risks (e.g., moved farther away from the receptors or sites to a location that affords reduced risk because of the characteristics of the site meteorology). Directional drilling to a target formation is one way of obtaining an offset on the surface that would reduce potential downwind concentrations. In some places, the siting and operation of sour-gas facilities are controlled by specific regulations. The Railroad Commission of Texas (1976) has adopted a regulation known as Rule 36; it prescribes safety measures for sour-gas facilities that could emit enough hydrogen sulfide to endanger nearby residents. Facilities are screened through the use of equations that estimate the distances to the 100- and 500-ppmv concentrations, based on an estimated emission rate. The safety measures stipulated (e.g., control equipment, contingency plan, etc.) depend on the exposure radii calculated for the well (Smith, 1977). Sour-gas facilities completed in Alberta, Canada, are required to have specific separation distances from houses and public facilities; the distances are defined by the potential amounts of hydrogen sulfide released (Energy Resources Conservation Board, 1981b).

Even if sour-gas wells are sited to minimize potential exposures, the problem of future population encroachment into high-risk areas still exists. This situation is of special concern for wells that are situated on the fringes of communities where residential growth is expected to occur over the life of the wells. Encroachment into "high-risk" zones can be limited by land-use zoning or by the preemptive ownership of lands around wells by the company that owns the well(s). Land-use restrictions obviously are less costly than land acquisition schemes; however, ownership should be considered in those instances where local or state governments do not adopt land-use controls.

A contingency plan that outlines the steps required once a release occurs is an essential tool in the management of health risks. It contains the protocols needed to protect workers and local residents from hazardous exposures. Important actions that should be addressed in contingency plans include the ignition of the sour gas to produce a buoyant plume of sulfur dioxide, notification and evacuation of residents, provision for emergency health care, post-release monitoring of gases, and site security. Well ignition is important because the buoyant plume produced after combustion essentially eliminates the risks of acute health effects because the ground-level concentrations of sulfur dioxide would not reach lethal levels. However, well ignition will not be possible if the gas contains elevated levels of carbon dioxide, which would effectively serve as a fire extinguisher. The potential for carbon dioxide-rich gases should be addressed in the contingency plan.

Of the remaining actions, public notification and health care merit special attention. Residents should be listed in contingency plans by distance and downwind sector so that notification can begin in the sectors downwind from the well. The meteorological conditions present and the nature of the release can also be compared with the health-risk estimates to determine whether there is a need for emergency health care in the downwind sectors. One problem that plagues safety planning related to hazardous gases is the lack of attention given to the consequences of sublethal exposures. The incidents at Bhopal, India, and Poza Rica, Mexico, have clearly shown that the numbers of people experiencing sublethal effects greatly exceed those with acute, life-threatening responses. This is important because the individuals with the sublethal effects are those that will overwhelm health-care facilities. As we have shown in the analysis of the sour-gas well, only the horizontal release would pose a risk of life-threatening concentrations; however, both release modes would result in subacute effects over a wide area. Contingency plans should specifically address measures needed to deal with those who experience sublethal effects. Medical personnel, for example, should be aware of the symptoms associated with both acute and subacute exposures and the appropriate methods of treatment.

Conclusions and Recommendations

The analysis and assessment of the health and environmental risks of a potential sour-gas release from a well can be viewed as a sequential process consisting of these primary elements:

- Estimation of the emission rate of hydrogen sulfide,
- Prediction of the downwind concentrations of hydrogen sulfide after an accidental release,
- Analysis of the potential health effects resulting from the predicted concentrations,
- Review of the safety measures and technologies required to minimize the health risks of a sour-gas release.

The quantification of the potential emission rate is most difficult for exploratory wells because of uncertainties regarding the productivity of the geologic formations that might be encountered and the composition of the natural gas in those formations. To deal with those uncertainties in a quantitative manner, we recommend a statistical approach in which an upper-bound emission rate is calculated from a lognormal distribution that is a product of two other lognormal distributions; one represents concentrations of hydrogen sulfide measured in natural gases in exploration regions, and the other represents the CAOF of wells completed into similar formations. We used the 98th cumulative percentile to define the upper-bound emission rate for assessing the hazards of an accidental gas release.

Gas discharge to the atmosphere through production tubing also should be considered because this type of a release is more likely to result in a horizontal release of gas. For exploratory wells, an estimate of this rate equals 40% of the CAOF. To support the use of the probabilistic approach for quantifying emissions of hydrogen sulfide from exploratory wells, we recommend that additional data be collected on the concentrations of hydrogen sulfide in natural gases from wells completed in the Overthrust Belt. In addition, we believe that additional work is warranted on the failure modes that would result in atmospheric discharges from well-head assemblies. Finally, we recommend that there be a closer relationship between the process of identifying and analyzing risks and the process of risk management. Such a linkage would help ensure that all of the adverse consequences of hazardous gas releases are averted or minimized.

Acknowledgments

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Table 1. Summary of the toxic effects of hydrogen sulfide on humans, based on animal studies as well as actual exposures to man.

Concentration[a]		Exposure	
ppmv	mg/m^3	time (s)	Effect
2000[b]	2880	3-10	Respiratory arrest, unconsciousness, pulmonary edema, or death
500-1000[b]	720-1440	~3-120	Respiratory arrest, unconsciousness, pulmonary edema, or death
250[c]	360	1220	Unconsciousness
150-250	216-360	--	Olfactory paralysis
50-300+	72-432	<3600	Eye irritation
100	144	--	Neurasthenic disorders
0.005	0.007	--	Median odor threshold

[a] For a pressure of 1 atm and a temperature of 15.6°C.

[b] Animal data (Haggard, 1925; Mitchell and Yant, 1925).

[c] Based on one incident (Ahlborg, 1951).

Table 2. Hydrogen sulfide in productive sour-gas formations in Overthrust Belt of western Wyoming and adjacent areas in Utah.[a]

Geologic formation	Number of samples	Mean mol% (g/m^3)	Std. dev. mol% (g/m^3)	Geometric mean mol% (g/m^3)	Geometric std. dev.
Phosphoria	4	11.9 (171)	3.6 (52)	11.4 (164)	1.4
Weber	5	13.7 (198)	5.6 (80)	12.8 (185)	1.5
Madison	12	13.2 (191)	9.3 (134)	10.2 (147)	2.2
Bighorn	5	1.2 (17)	0.6 (9)	1 (14)	1.8

[a] From Layton *et al.*, 1983.

Table 3. Coefficients for the power-law equation of σ_y for distances from 100 m up to 10,000 m (Texas Air Control Board, 1979).[a]

Atmospheric stability class	Power-law coefficient	
	a	b
A very unstable	0.495	0.873
B moderately unstable	0.310	0.897
C slightly unstable	0.197	0.908
DD neutral (day)	0.122	0.916
DN neutral (night)	0.122	0.916
E slightly stable	0.0934	0.912
F moderately stable	0.0625	0.911

[a] $\sigma_y = ax^b$ where x is the downwind distance in meters.

Table 4. Coefficients for the power-law equation of σ_z (Texas Air Control Board, 1979).[a]

	Downwind distance (m)					
	$100 < x \leq 500$		$500 < x \leq 5000$		$5000 < x \leq 50,000$	
Atmospheric stability class	Power-law coefficient					
	c	d	c	d	c	d
A very unstable	0.0383	1.281	0.0002539	2.089	0.0002539	2.089
B moderately unstable	0.1393	0.9467	0.04936	1.114	0.04936	1.114
C slightly unstable	0.1120	0.9100	0.1014	0.926	0.1154	0.9109
DD neutral (day)	0.0856	0.8650	0.2591	0.6869	0.7368	0.5642
DN neutral (night)	0.0818	0.8155	0.2527	0.6341	1.297	0.4421
E slightly stable	0.1094	0.7657	0.2452	0.6358	0.9204	0.4805
F moderately stable	0.05645	0.8050	0.1930	0.6072	1.505	0.3662

[a] $\sigma_z = cx^d$ where x is the downwind distance in meters.

Table 5. Pasquill-Gifford stability categories and wind speed classes used to characterize dispersive characteristics of the atmosphere.

Atmospheric stability class	Description	Wind-speed class	Range of wind velocities (m/s)
A	Very unstable	1	0 to 1.6
B	Moderately unstable	2	1.7 to 3.4
C	Slightly unstable	3	3.5 to 5.4
DD	Neutral (day)	4	5.5 to 7.8
DN	Neutral (night)	5	7.9 to 10.7
E	Slightly stable	6	>10.7
F	Moderately stable		

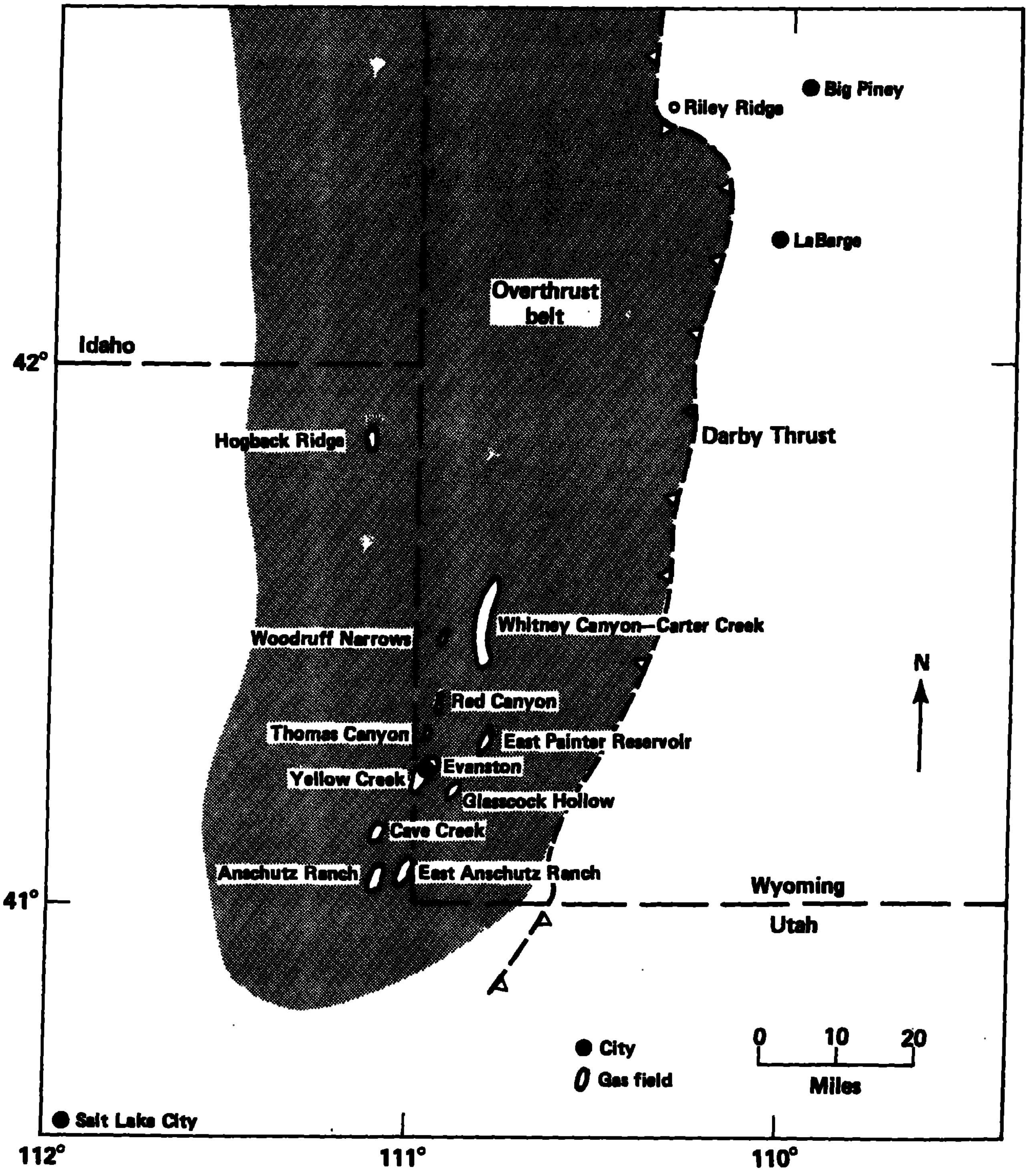
Fig. 1. Location of natural gas fields in Overthrust Belt of western Wyoming and adjoining areas in Utah (after Ver Ploeg and De Bruin (1982) and Petroleum Information Corporation (1981)).

Fig. 2. Subsurface components of a completed sour-gas well.

Fig. 3. Upper-bound estimates of the probability of incurring acute (life-threatening) health effects after an accidental, horizontal release of sour gas from a well in the vicinity of Evanston, Wyoming. To estimate the actual risks in the four downwind sectors, (i.e., the N, NE, E, and SE sectors) each curve value must be multiplied by the probability of an accidental release.

Fig. 4. Upper-bound estimates of the probability of incurring acute (life-threatening) health effects after an accidental, horizontal release of sour gas from a well in the vicinity of Evanston, Wyoming. To estimate the actual risks in the four downwind sectors (i.e., NW, W, S, and SW), each curve value must be multiplied by the probability of an accidental release.

Fig. 5. Upper-bound estimates of the probability of incurring sublethal health effects in the NE downwind sector after an accidental, vertical release of sour gas from a well in the vicinity of Evanston, Wyoming. To estimate the actual risks, each curve value must be multiplied by the probability of an accidental release.



Big Piney
Riley Ridge
LaBarge
Overthrust belt
Idaho
42°
Darby Thrust
Hogback Ridge
Whitney Canyon—Carter Creek
Woodruff Narrows
N
Red Canyon
Thomas Canyon
East Painter Reservoir
Evanston
Yellow Creek
Glasscock Hollow
Cave Creek
Anschutz Ranch
East Anschutz Ranch
Wyoming
41°
Utah
City
Gas field
0
10
20
Miles
Salt Lake City
112°
111°
110°

Figure 1

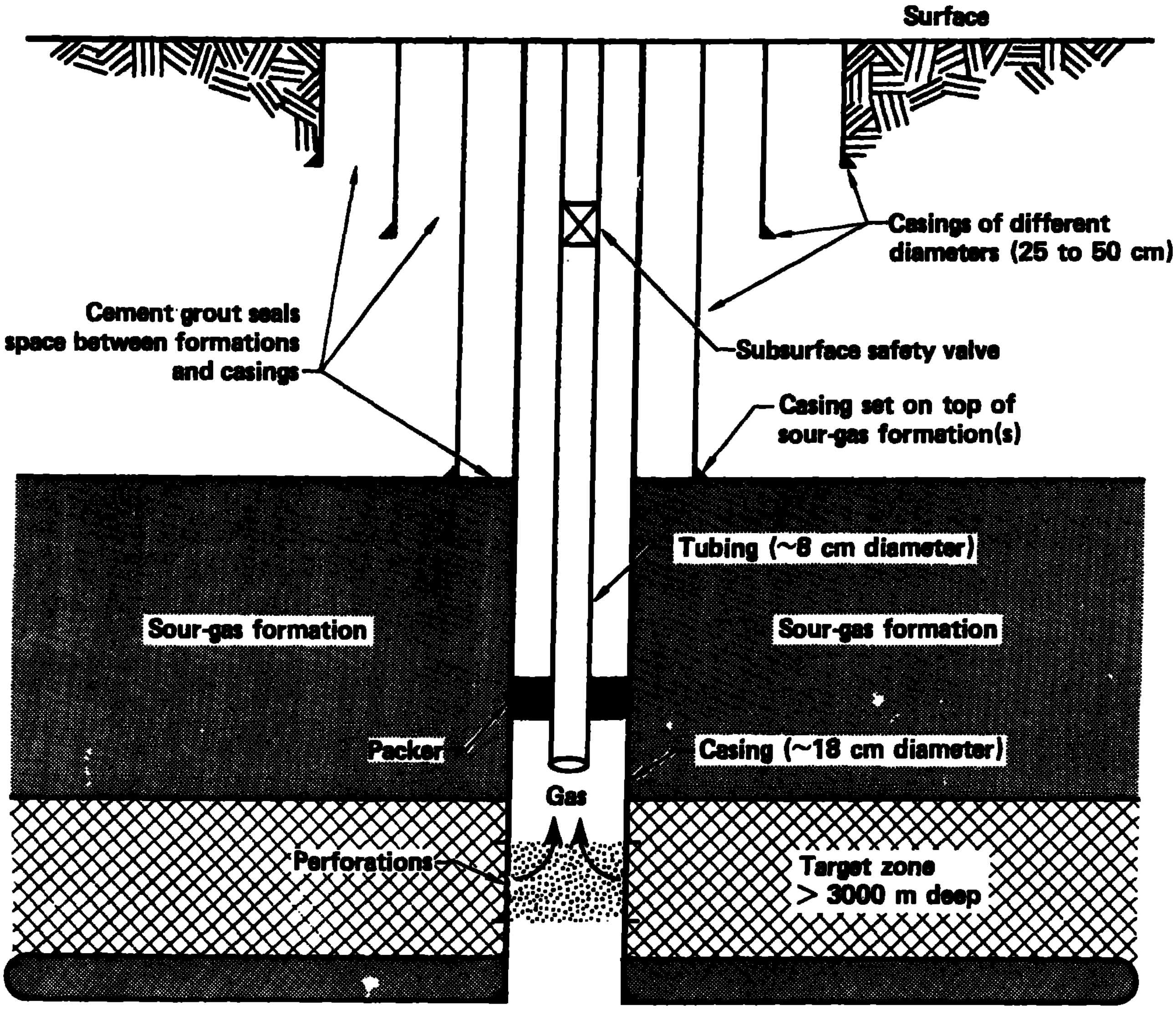
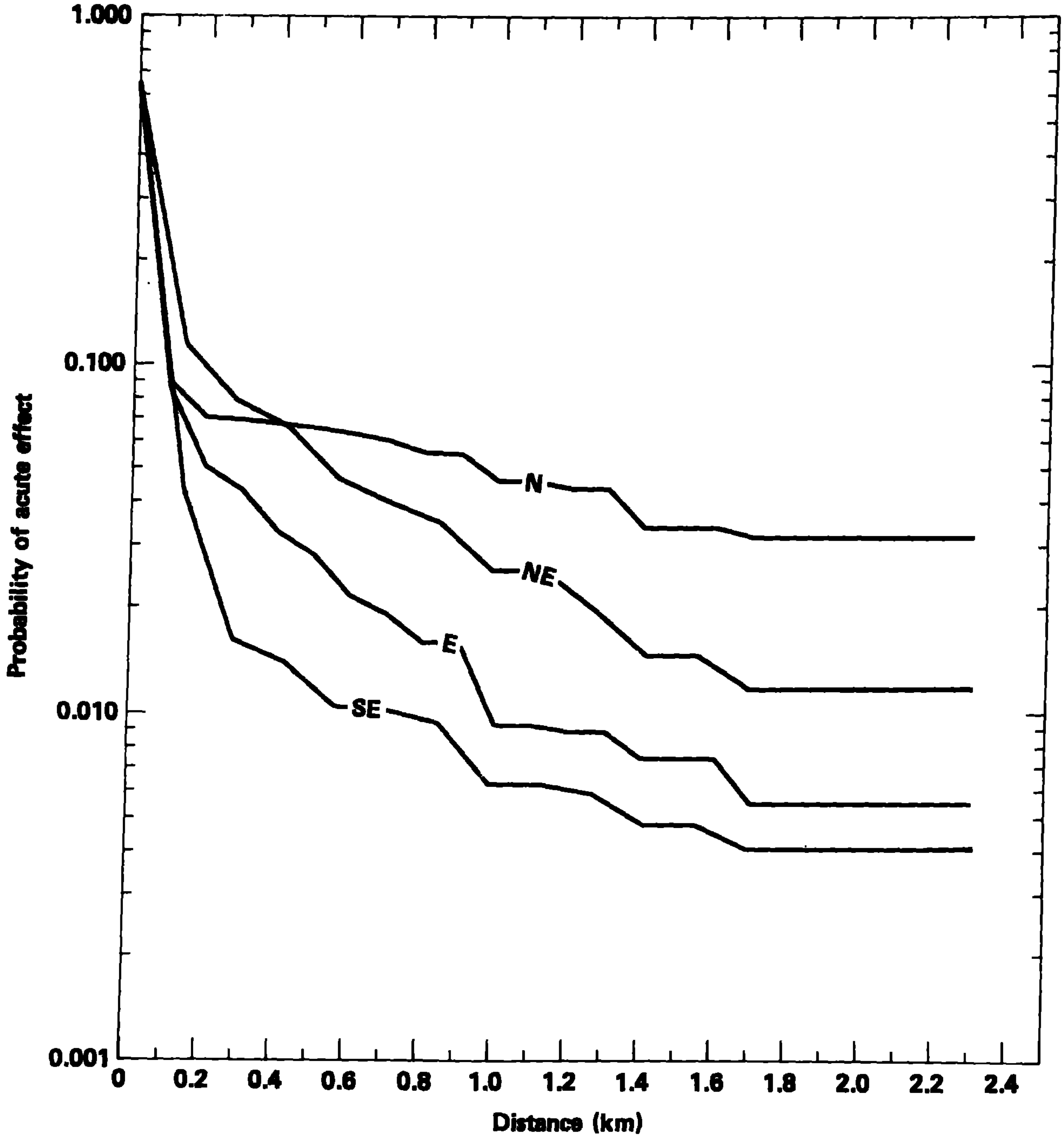

Surface
Casings of different diameters (25 to 50 cm)
Cement grout seals space between formations and casings
Subsurface safety valve
Casing set on top of sour-gas formation(s)
Tubing (~8 cm diameter)
Sour-gas formation
Sour-gas formation
Packer
Casing (~18 cm diameter)
Gas
Perforations
Target zone > 3000 m deep

Figure 2



1.000
0.100
0.010
0.001
Probability of acute effect
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
Distance (km)
N
NE
E
SE

Figure 3

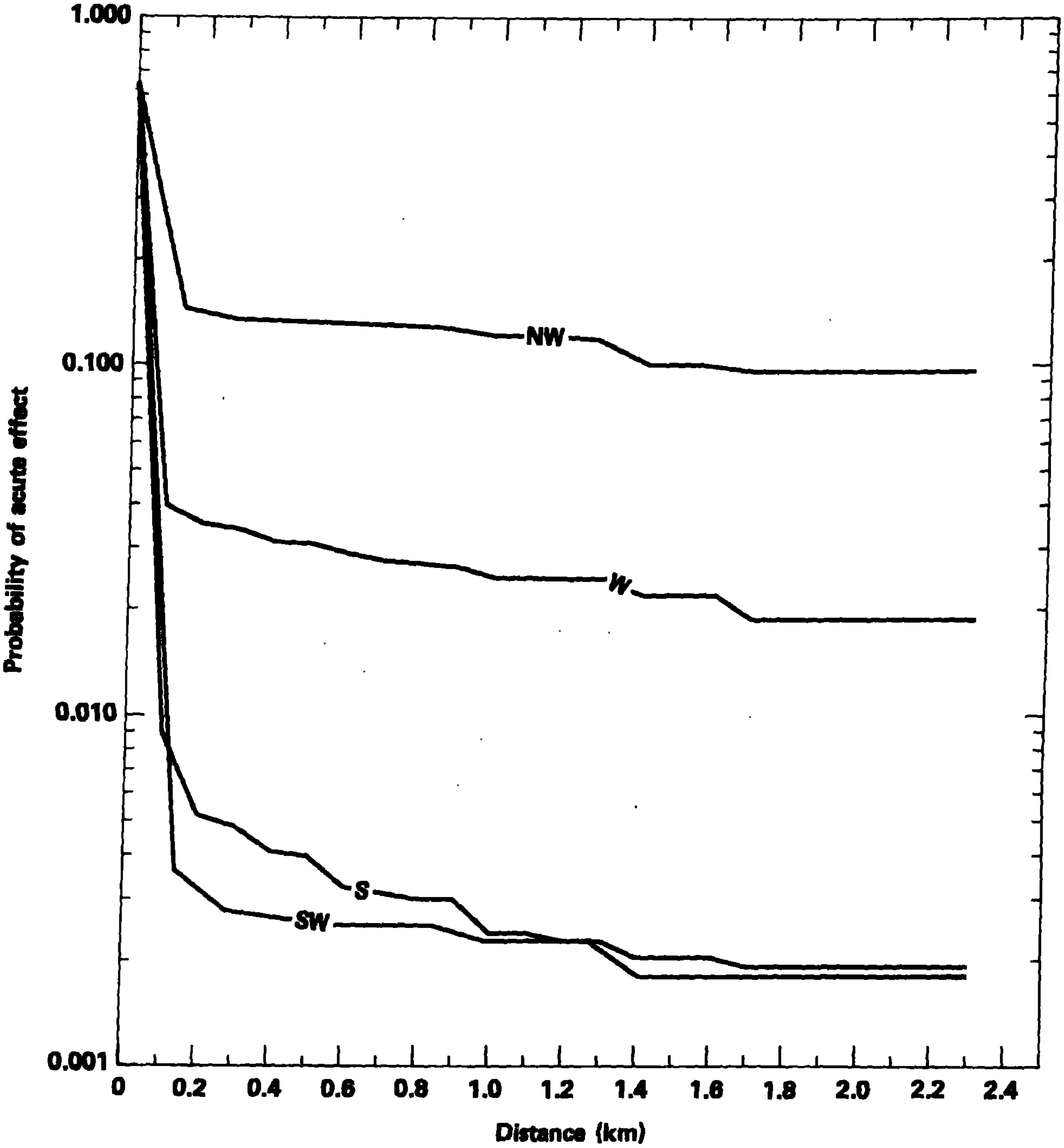

1.000
0.100
0.010
0.001
Probability of acute effect
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
Distance (km)
NW
W
S
SW

Figure 4

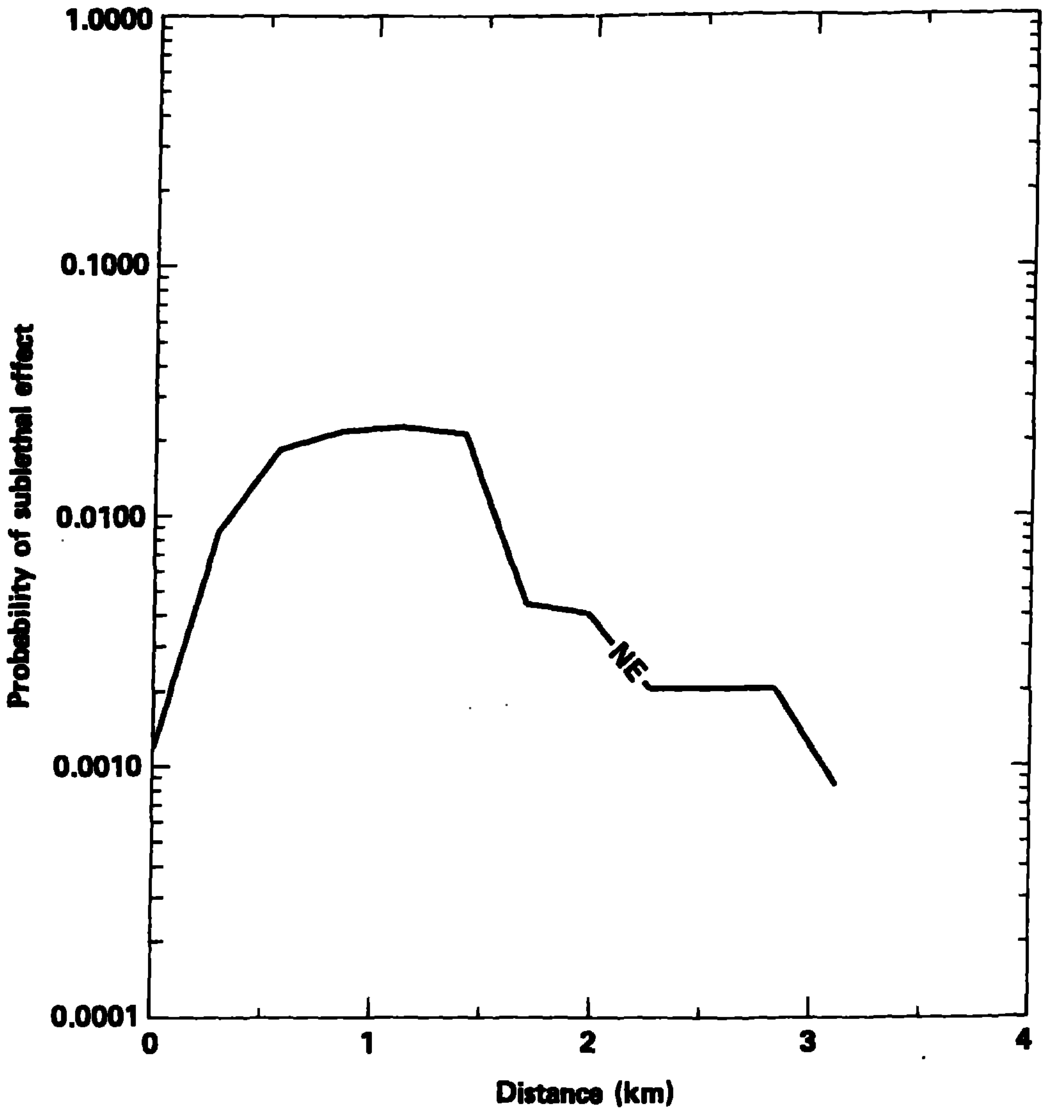

1.0000
0.1000
0.0100
0.0010
0.0001
Probability of sublethal effect
0
1
2
3
4
Distance (km)
NE

Figure 5